# X-1 to X-Wings
# Developing a Parametric Cost Model

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**NASA - Armstrong Flight Research Center**

# Introduction

- In today's cost constrained environment NASA needs a X-Plane data base and parametric cost model that can quickly provide a rough order of magnitude cost predictions for experimental aircraft.

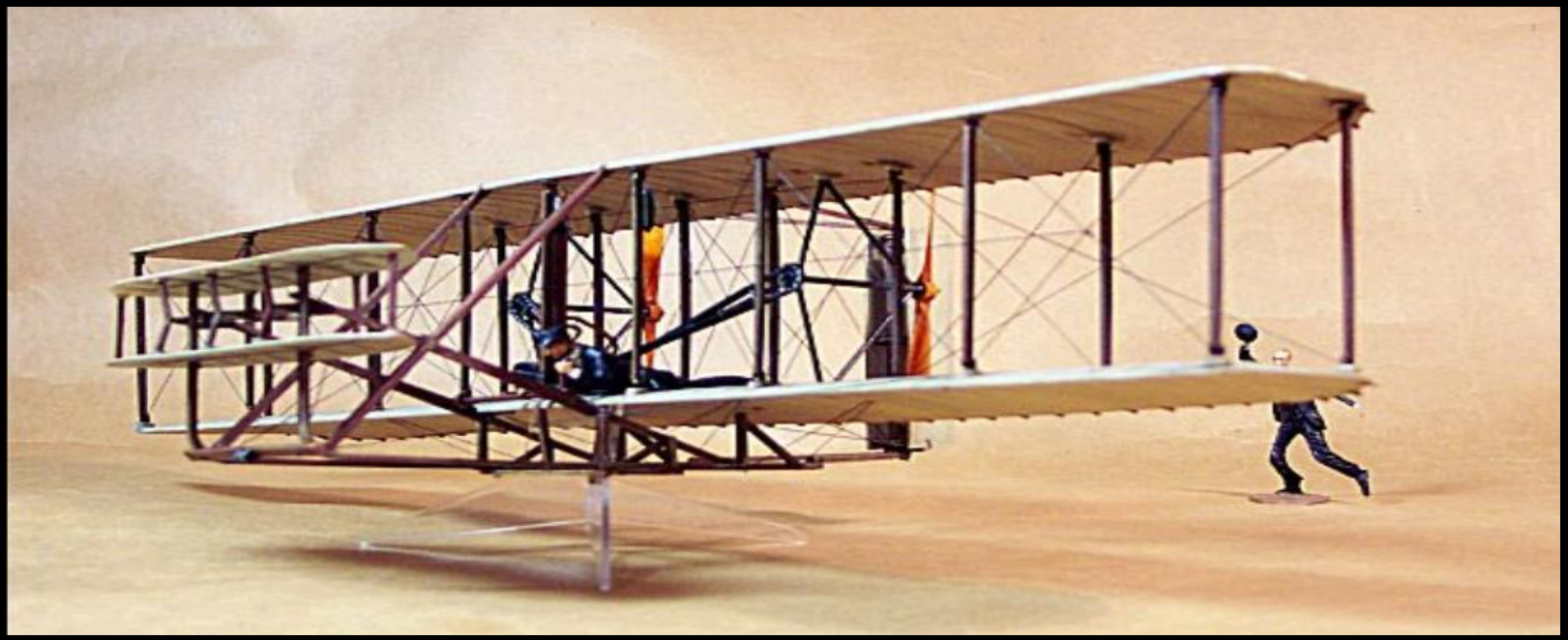
- The model should be based on critical aircraft design parameters, such as weight, size, and speed, as well as some sort of complexity factor..

- It's commonly known among cost engineering professionals, both government and industry that weight based CERs have the highest correlation.

- Last fall 2014 - the authority was given on a non-interference basis to develop an X-Plane Parametric Cost Model.

- Then early spring 2015 – I was given opportunity to hire a Summer Internship to assist in developing CERs using Regression Analysis.

# Challenges in getting cost data



Throughout history every aircraft manufacturer, starting with the Wright brothers, has weighed their aircraft. The original Wright Flyer (Flyer I) weighed 604.1 pounds. A military version of the aircraft (Flyer III), capable of carrying one passenger, was procured by the Army Signal Branch for $30,000, thus establishing the first CER at $49.66 per pound.

# The Story behind the X-1 Bell

I walked into work everyday for 10 years. One day I took the initiative to put my thoughts and my training into action with the question; what was the cost to design, build and fly the 1952 Bell X-1E ?

I made a quick cost estimate using the Wright Flyer weight CER and adjusted for inflation. This gave me an estimate of $1.8 million in FY52 dollars, which is reasonably close to the actual cost.

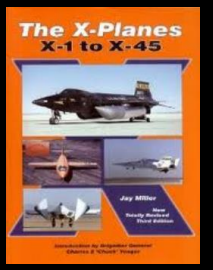
# Challenges in getting cost data

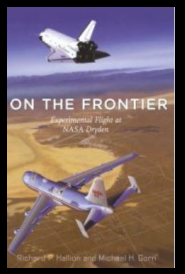
**Timeline**

- 1940's  50's, 60's & 70's. . . Were basically joint-funded Programs;
  - National Advisory Committee for Aeronautics (NACA)
  - National Aeronautics and Space Administration (NASA)
  - U.S. Army, and various U.S. Air Force
- Salary Dollars were paid under a different "Appropriation".
- NASA Dryden/Armstrong was under Ames until January 1994.
- Full Cost Accounting did not go into affect until 2002.
- Some Project Managers (PM) have volumes of cost data stored away in their cabinets.
  - Organized in 3-ring binders
  - Organized by burning; technical, scope, schedule, and cost data onto CDs
- NASA has a Cost Analysis Data Requirement (CADRe) for projects subject to NPR 7120.5E.
- In general, CAD and NASA Aeronautic Centers will cover CADRe for 7120.8 Research and Technology Program and Projects i.e. X-Planes.

# Source of the Data

- NASA Technical Libraries
  - Armstrong's Technical Reference Library
  - Marshall Space Flight Center – Library "Redstone"
- Various publications "Books" specifically written on X-Planes
  - "The X-Planes"; written by Jay Miller
  - "On the Frontier"; written by Richard Hallion & Michael Gorn.
- Subject Matter Experts
  - Dr. Joseph Haymaker
  - 3rd Parties "Cost Research" Companies
- Government Accountability Office (GAO)
  - Various Cost Reports on X-Planes
- Industrial Partners or various Aeronautical Manufactures
  - Proprietary and "thin-slicing" the data
- Wikipedia and other "on-line" sources
  - Beware of the information and document the source, date, and URL



# Hierarchal Cataloging of the data

- Some of the X-planes had three or mores sources of Cost Data
  - For Example: NASA Technical Data, GAO, Hamaker; for the same plane
  - How does the Cost Engineer know who's data is correct?
- The entire set of X-Planes parameters are now catalog in an Excel data base with a word document linked in a separate folder serving as the source document.
- Source documents are in Word format
  - **Name** of the person collecting the data
  - **Date** the source was collected
  - **URL** name if the source was collected on-line
    - Copy of the entire online source document includes references.
    - Note: a data element appeared to be changed within a 1 year time span.
- Hierarchy currently being used for Source Data

1.) Government Source (Technical Libraries) go first-in-line.

2.) People associated in collecting Cost for NASA or for the Government.

3.) Thin-slicing, Wikipedia and other on-line forums.

# Advance Composite Materials

- Advance Composite Materials (ACM) have gone a long way since the creation of carbon fiber and epoxy.
- Hand Lay-up versus Auto-Clave composite “Sandwich” Manufacturing
  - Hand-layup - is the process were resins are impregnated by hand in the form of woven, knitted, stitched or bonded fabrics. Hand-lay up process usually accomplished by rollers or brushes and cooked in a warm “unpressured oven”, cured under standard atmospheric conditions.
  - Autoclave - eliminates voids by placing the layup within a closed mold and applying vacuum, pressure, and heat.
- ACM aircraft manufactures are replacing 30,000 or more rivets and other components that were used by earlier aircraft manufacturing processes.

# Cost of using Advance Composite Materials for prototyping X-Planes

- Large and small aircraft manufactures are using Advance Composite Materials.
  - Reports are coming in with a 30% cost saving from aircraft companies using Composites rather than Aluminum and Rivets.
  - Yes, there were known problems with adhering process in the past – which now seems to be fixed.
- The current vision at NASA's Aeronautical Research Centers are to **D**esign, **B**uild and **F**ly "One-of-a kind" research X-Planes every 2 to 3 years.
- Rapid Prototyping from Design to 1st Flight is expected.
- NASA needs to build-in "concurrent system engineering" into the process including; Preliminary Design Reviews (PDRs), Critical Design Reviews (CDRs), "Air-worthiness", and Flight Readiness Reviews (FRRs)
- Eliminate the need for "Unidentified Future Expenses (UFE).

# Future State

- Twin Glider Assisted Launch System (TGALS) has currently been priced using the earlier algorithms of Armstrong's Parametric Cost Model.

- Show a 2 minute conceptual flight demo video
- https://www.youtube.com/watch?v=0hEnYyykaL8

# Parametric Cost Modeling

- Assumptions
  - Cost can be predicted by a few design parameters.
  - Cost includes the initial design to first flight.
- Parameters
  - Technical and performance parameters for 22 experimental aircraft
    - Dry Weight, Takeoff Weight
    - Length, Wing Span, Wing Area
    - Mach, Thrust, Speed Regime
    - Maximum Altitude, Range
    - Material, Number of Engines, Crew size
- Goal
  - Identify the best parameters
  - Develop the “best fit” R2 value greater than .80

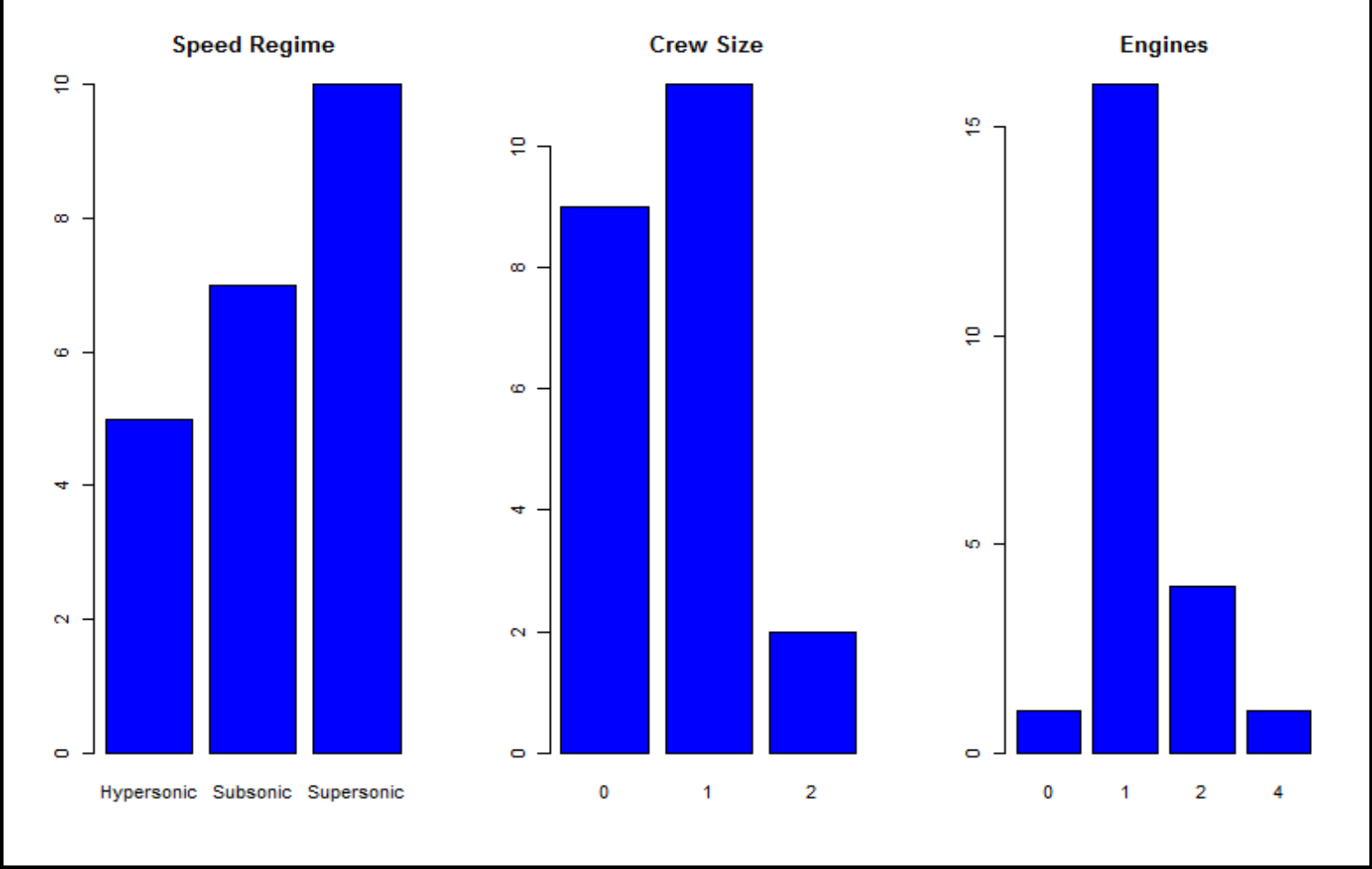
# Linear Regression

- Supervised learning
- Conceptually simple
- $Y_j = \beta_0 + \beta_1 X_{1j} + \beta_2 X_{2j} + \ \ldots + \beta_n X_{nj} + \varepsilon_j$
- Assumptions
  - Expected value of Y is a linear function of the X's
  - Unexplained variations in Y are independent and normally distributed
  - All errors in Y measurements have the same variance

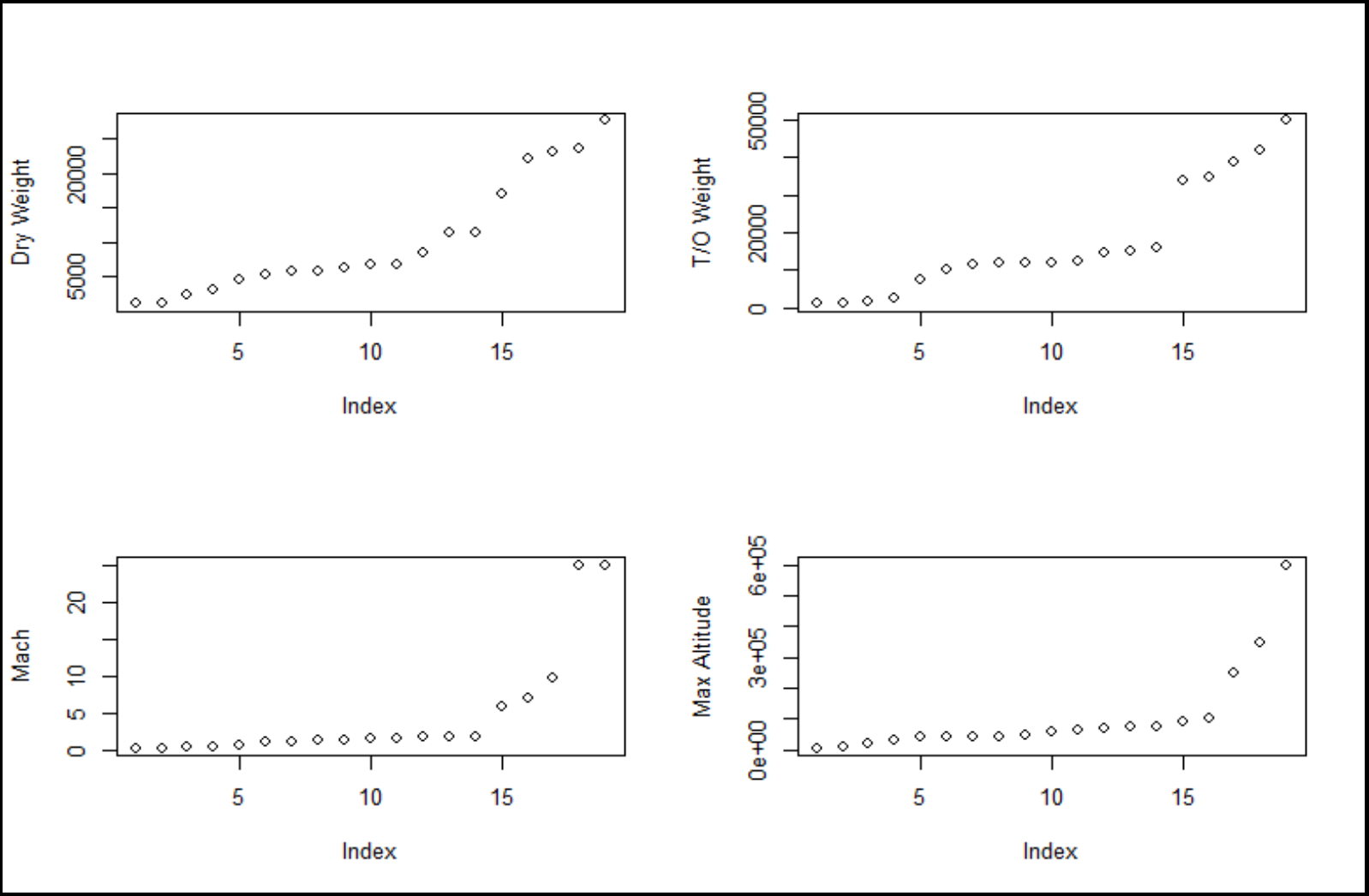
# Summary of Variables

| Statistic | Mean | St. Dev. | Min | Max |
|---|---|---|---|---|
| Cost | 357.97 | 489.77 | 12 | 1,600 |
| Dry.Wt | 11,102.36 | 9,222.96 | 377 | 28,814 |
| Length | 34.56 | 16.86 | 7.42 | 69.25 |
| Height | 11.26 | 4.39 | 3.13 | 23.75 |
| TO.Wt | 17,583.54 | 15,296.72 | 480 | 50,000 |
| Range | 1,784.05 | 5,307.26 | 1 | 25,000 |
| Max.Speed | 2,284.76 | 4,169.56 | 172.50 | 19,030 |
| Mach | 4.12 | 7.17 | 0.23 | 25 |
| Max.Altitude | 94,489.54 | 138,593.20 | 5,000 | 599,808 |
| Thrust | 18,385.14 | 19,559.06 | 0.50 | 60,000 |
| Wing.Span | 23.97 | 18.93 | 0.50 | 77.58 |
| Wing.Area | 207.10 | 160.65 | 0.50 | 590 |

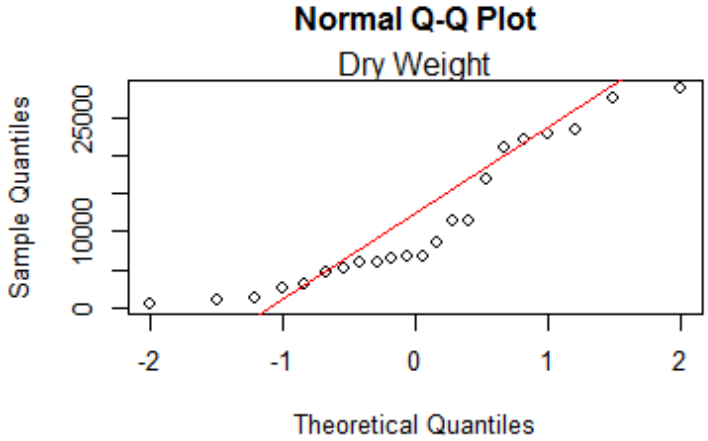
# Categorical Predictors

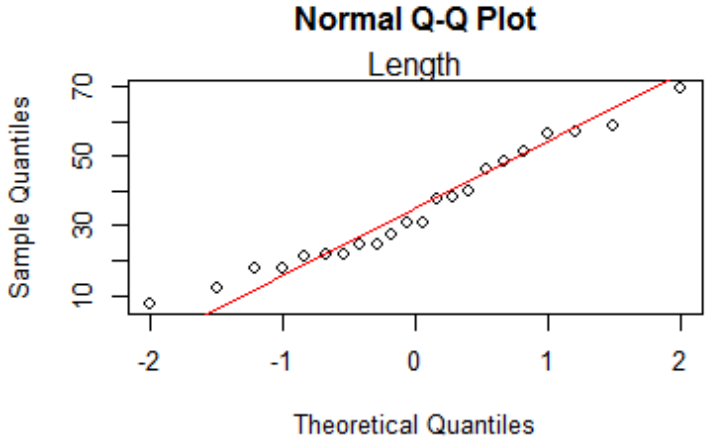


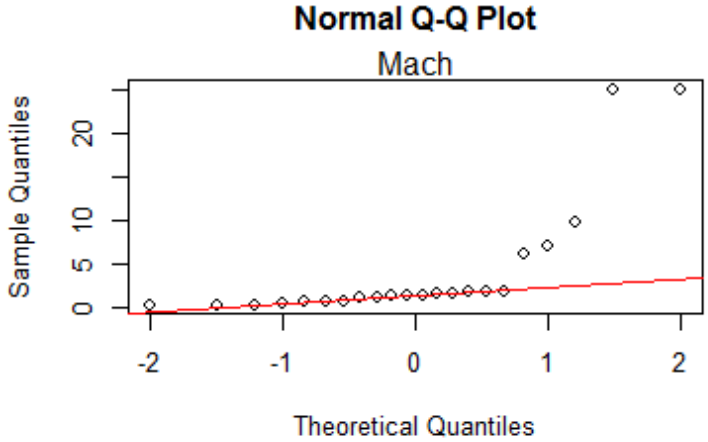
# Continuous Predictors

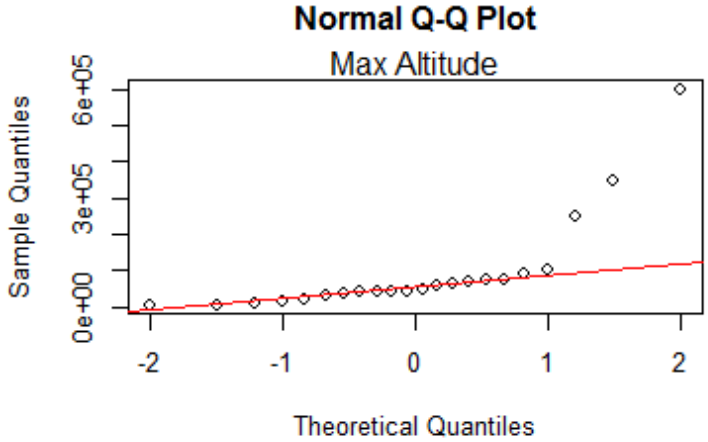


# Distribution: Original Data

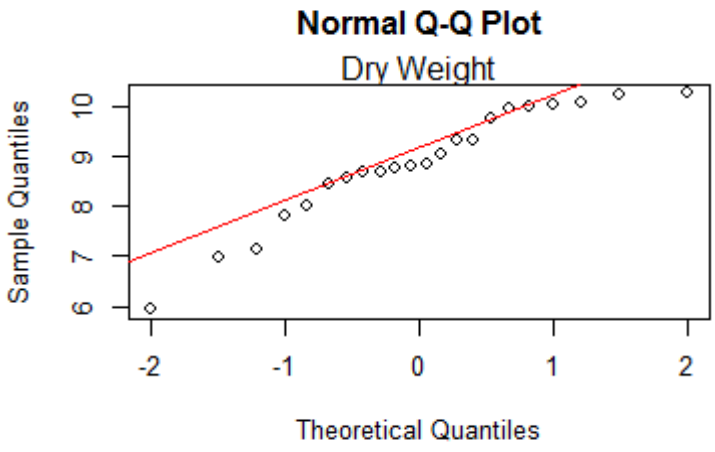


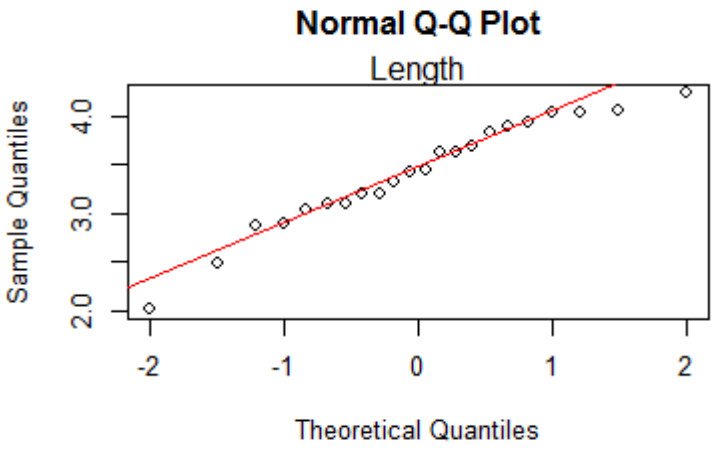



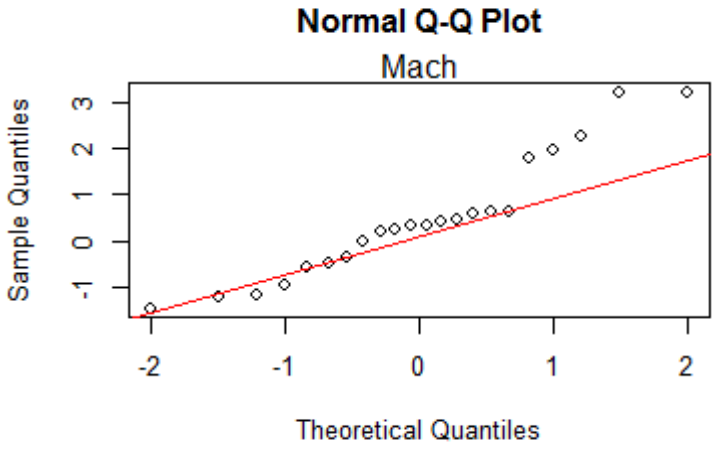



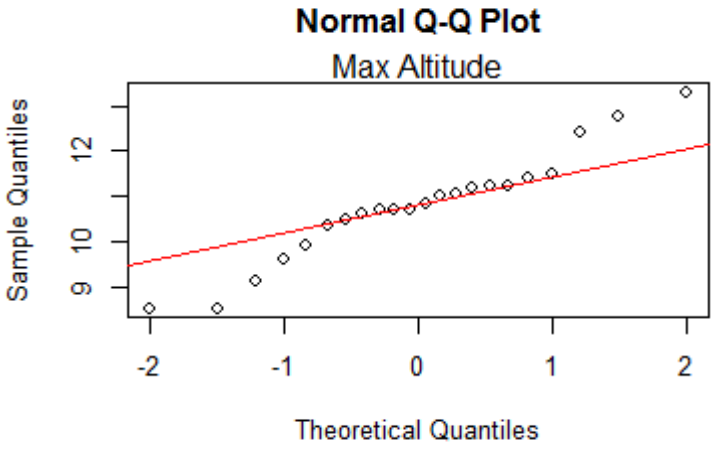



# Distribution: Log-Transformed Da

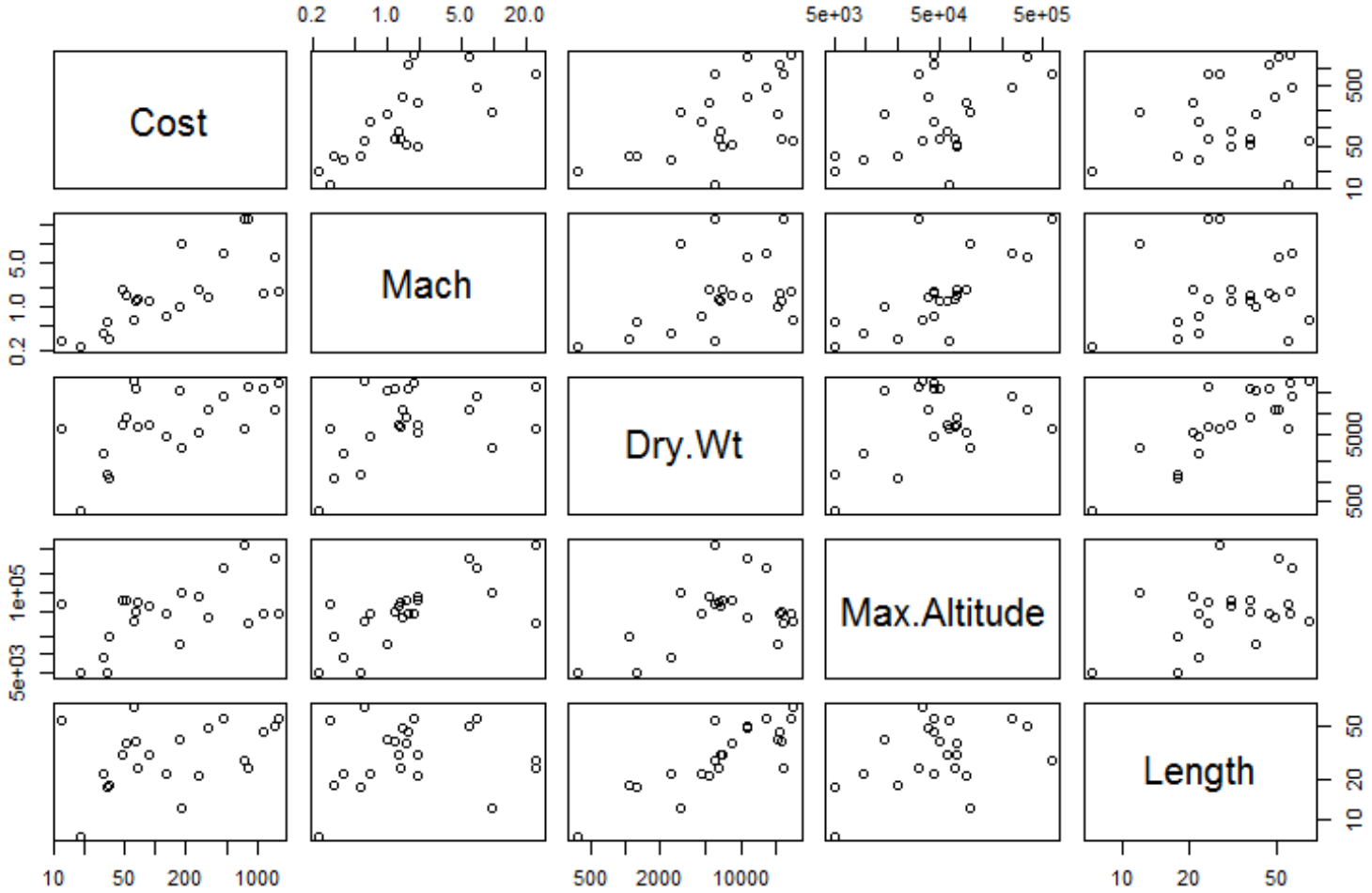


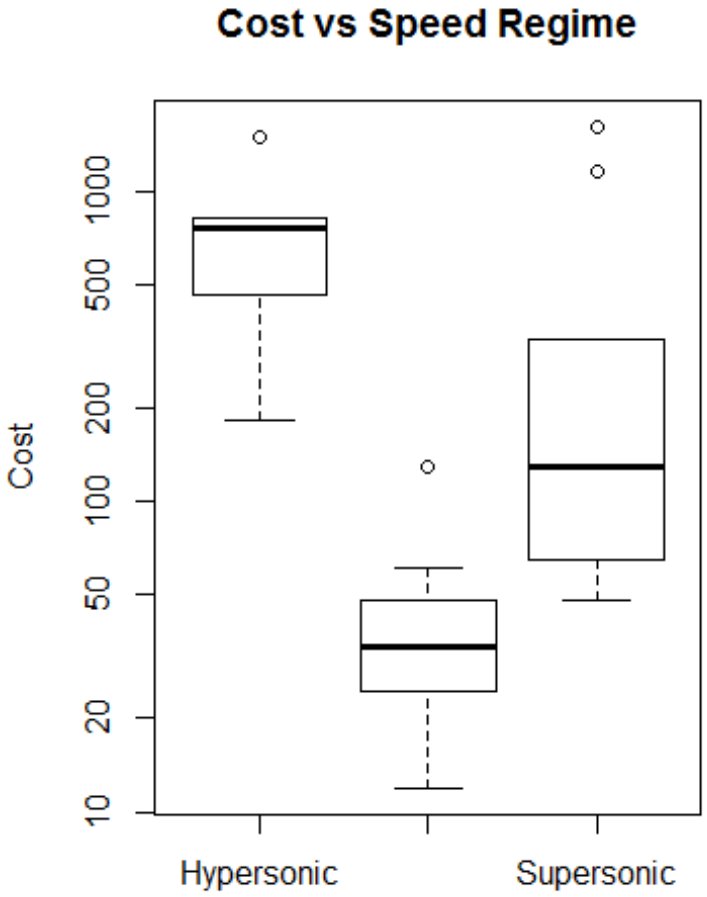



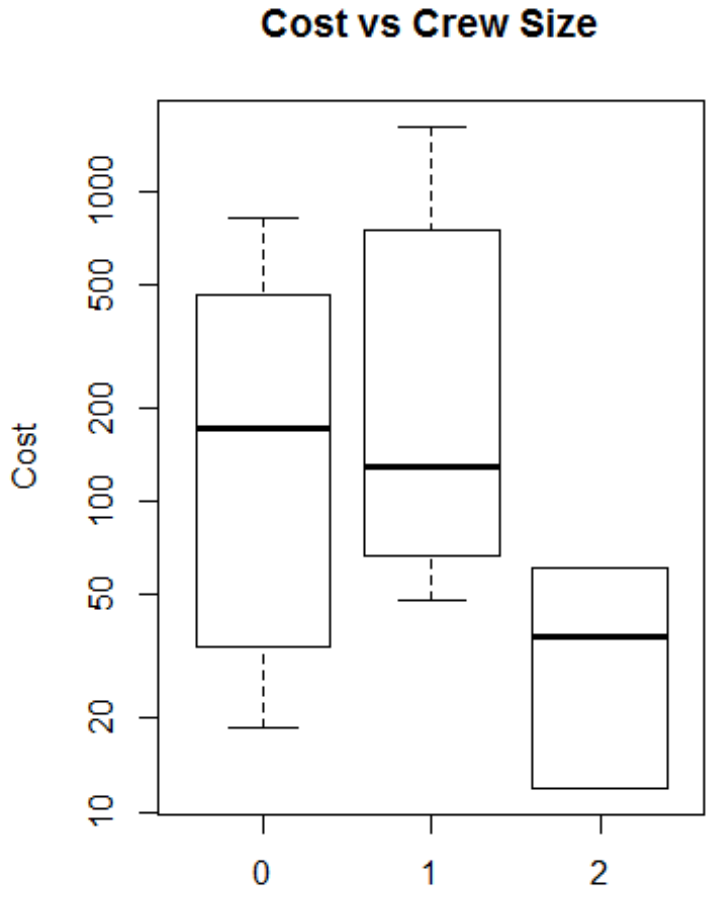



# Pairwise Scatter Plots

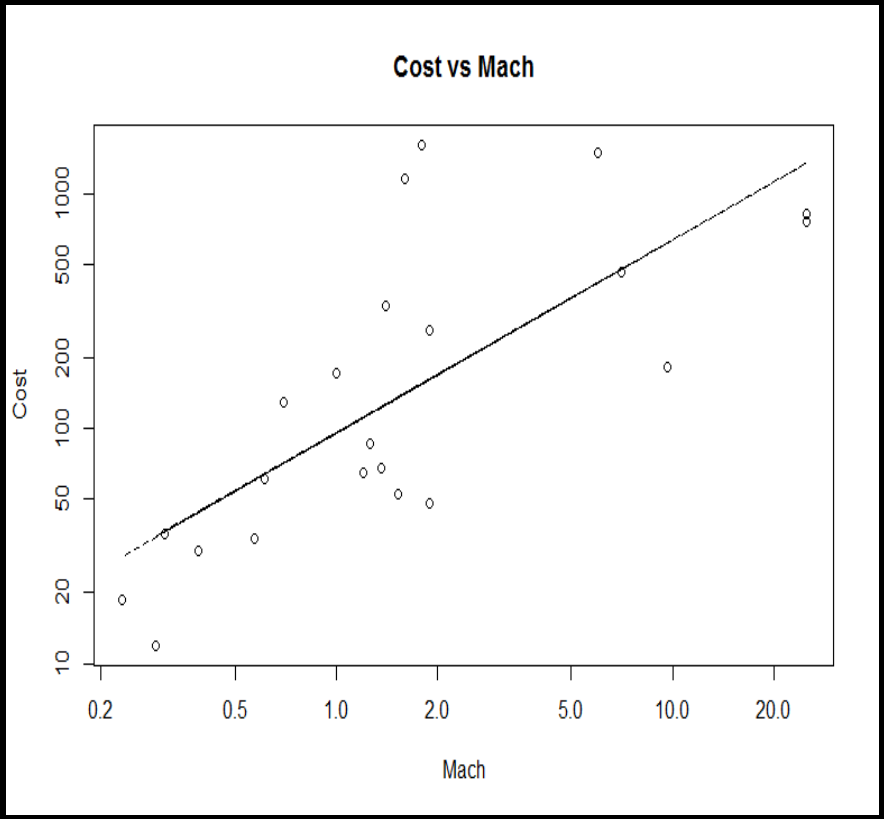


# Cost vs Categorical Predictor



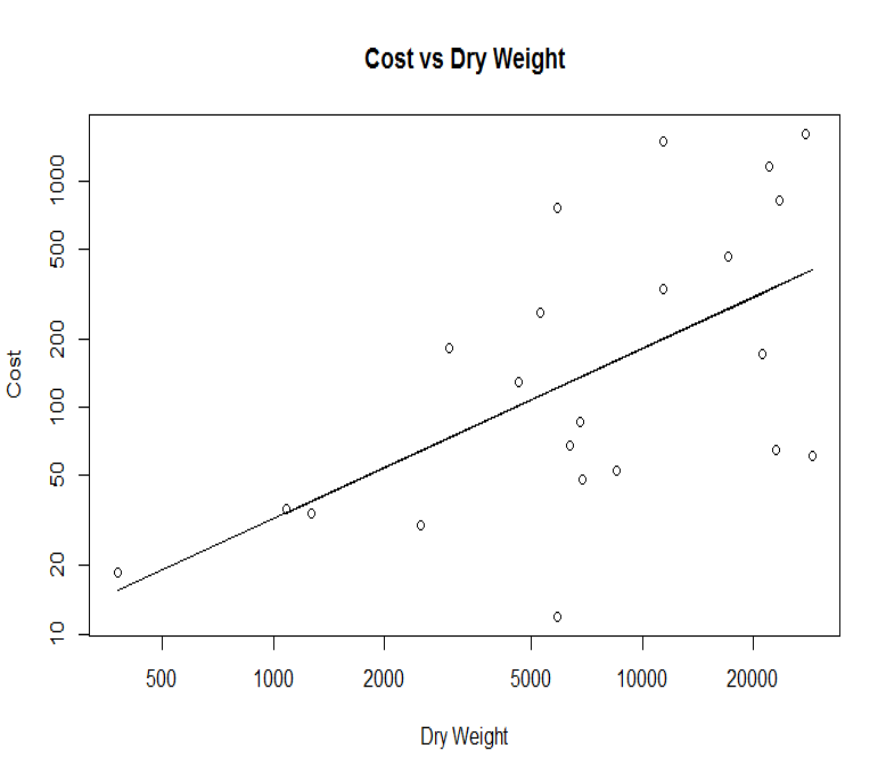



# Cost vs Mach




```
Cost ~ Mach

Residuals:
    Min      1Q  Median      3Q     Max
-1.2106 -0.5649 -0.3293  0.5581  2.3363

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   4.5592     0.2276  20.034 1.05e-14 ***
Mach          0.8205     0.1659   4.946 7.79e-05 ***
---

Residual standard error: 1.007 on 20 degrees of freedom
Multiple R-squared:  0.5501,    Adjusted R-squared:  0.5276
F-statistic: 24.46 on 1 and 20 DF,  p-value: 7.79e-05
```

# Cost vs Dry Weight



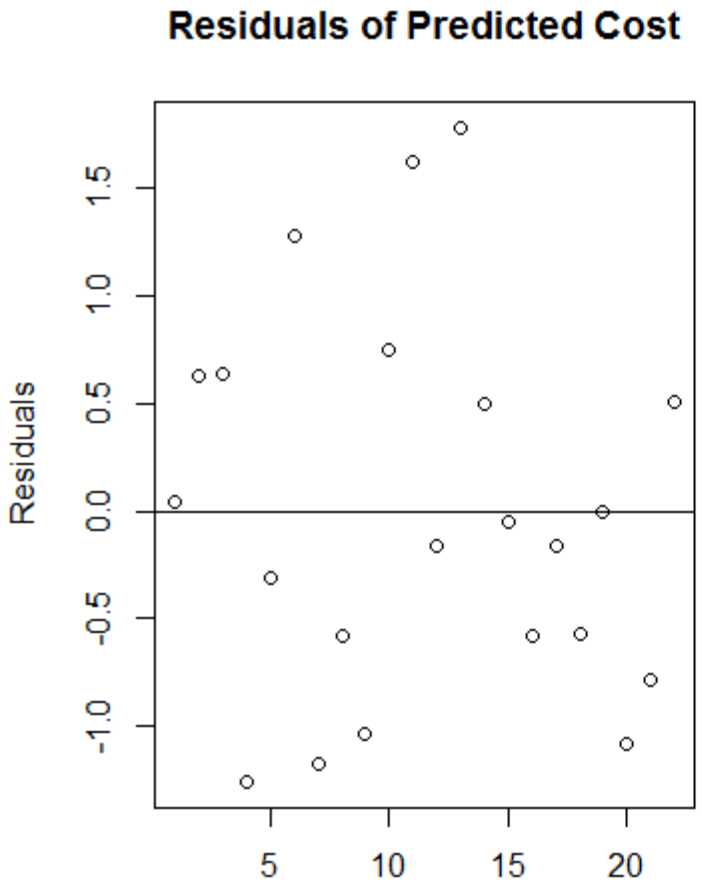

```
Cost ~ Dry.Wt

Residuals:
    Min      1Q  Median      3Q     Max
-2.3180 -0.7239  0.1129  0.8535  2.0023

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -1.7177     2.0576  -0.835  0.41369
Dry.Wt        0.7516     0.2307   3.258  0.00393 **
---

Residual standard error: 1.213 on 20 degrees of freedom
Multiple R-squared:  0.3468,    Adjusted R-squared:  0.3141
F-statistic: 10.62 on 1 and 20 DF,  p-value: 0.003934
```

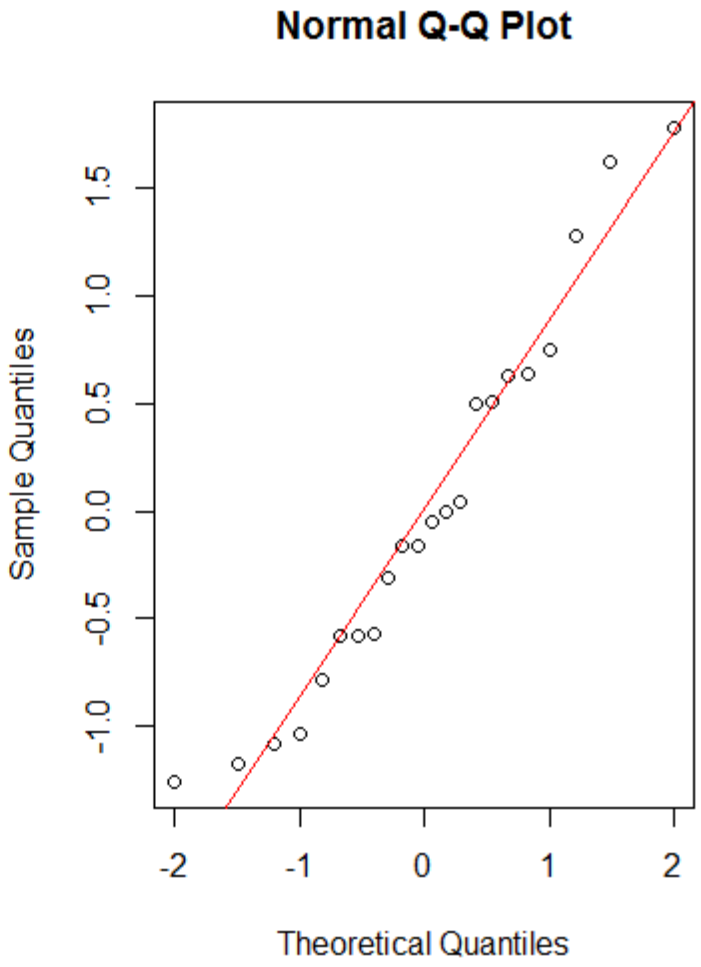
# Multiple Regression Model

```
Cost ~ Mach + Dry.Wt

Residuals:
    Min      1Q  Median      3Q     Max
-1.2519 -0.5805 -0.1066  0.5989  1.7749

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   0.8883     1.7024   0.522 0.607842
Mach          0.6630     0.1687   3.930 0.000899 ***
Dry.Wt        0.4229     0.1946   2.173 0.042652 *
---

Residual standard error: 0.9243 on 19 degrees of freedom
Multiple R-squared:  0.6397,   Adjusted R-squared:  0.6017
F-statistic: 16.86 on 2 and 19 DF,  p-value: 6.146e-05
```

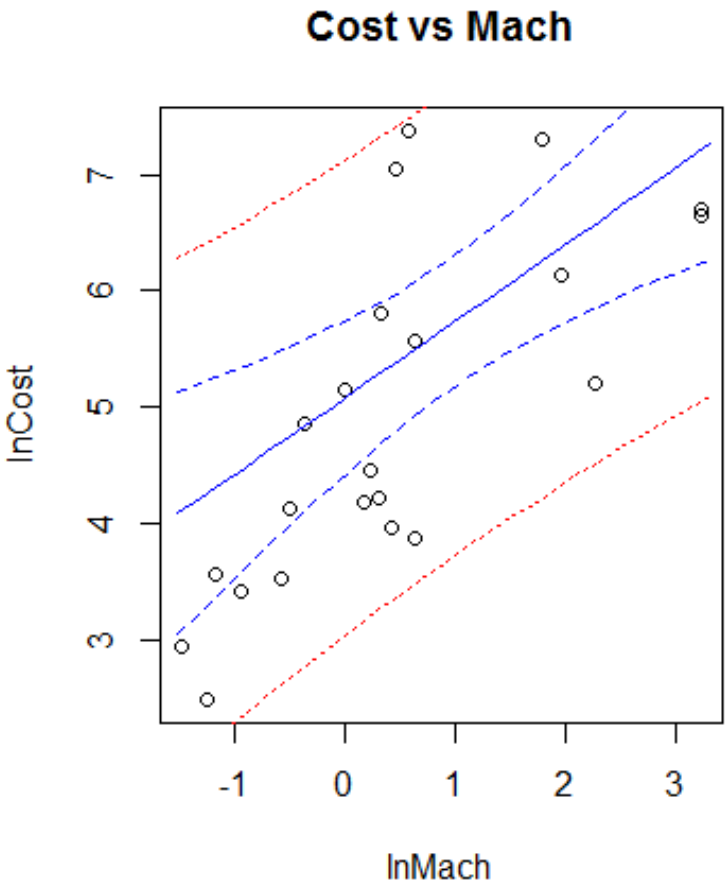
| | Cost | Mach | Dry.Wt | Max.Alt | Length |
|---|---|---|---|---|---|
| Cost | 1.00 | 0.74 | 0.59 | 0.54 | 0.36 |
| Mach | 0.74 | 1.00 | 0.43 | 0.70 | 0.12 |
| Dry.Wt | 0.59 | 0.43 | 1.00 | 0.43 | 0.83 |
| Max.Al | 0.54 | 0.70 | 0.43 | 1.00 | 0.42 |
| Length | 0.36 | 0.12 | 0.83 | 0.42 | 1.00 |

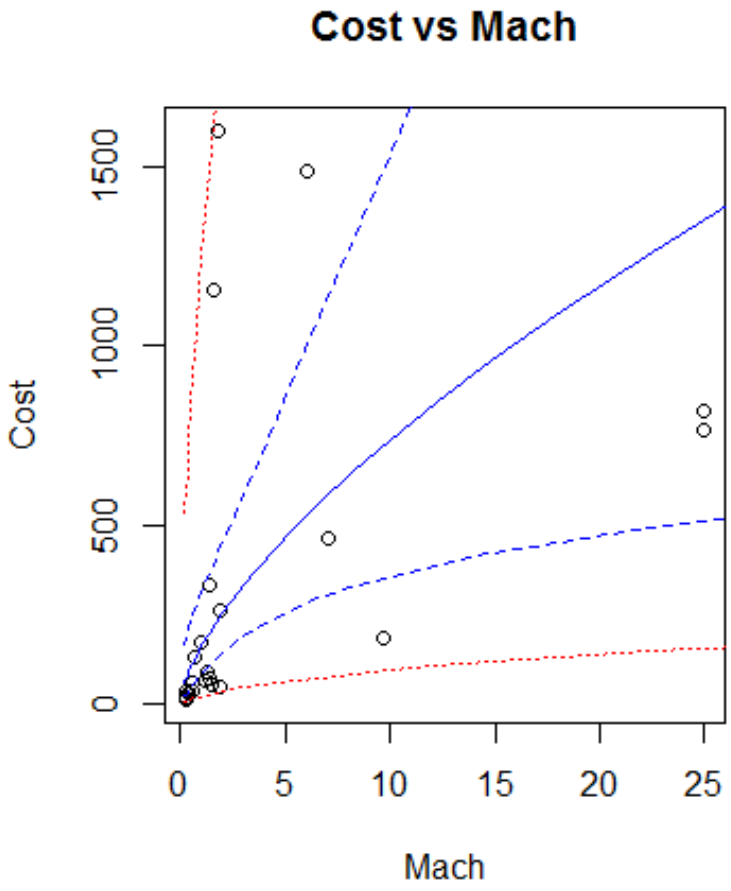
# Model Assumptions



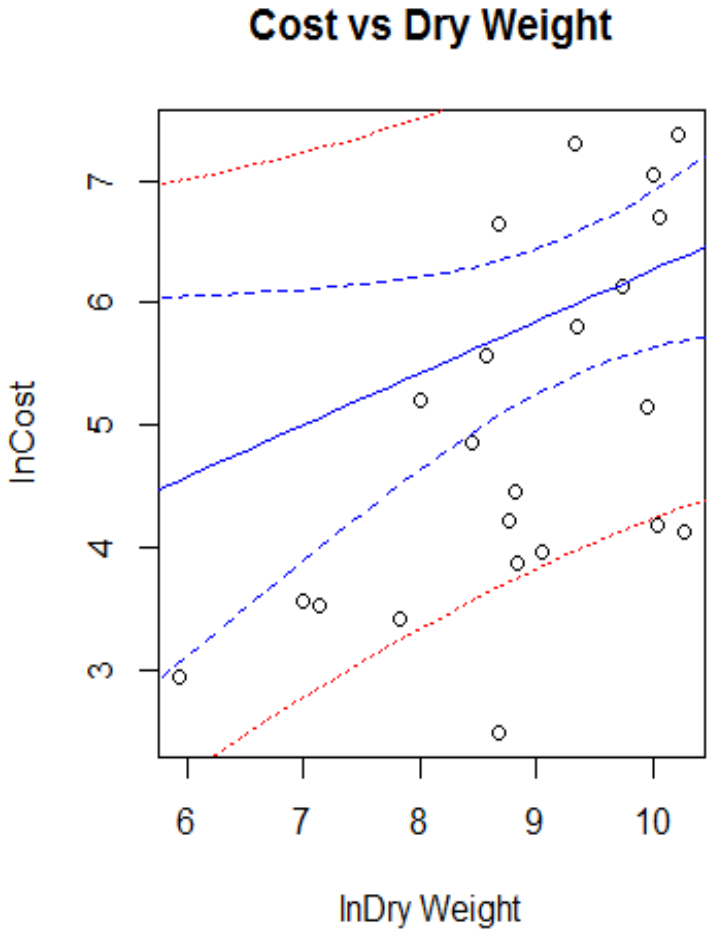



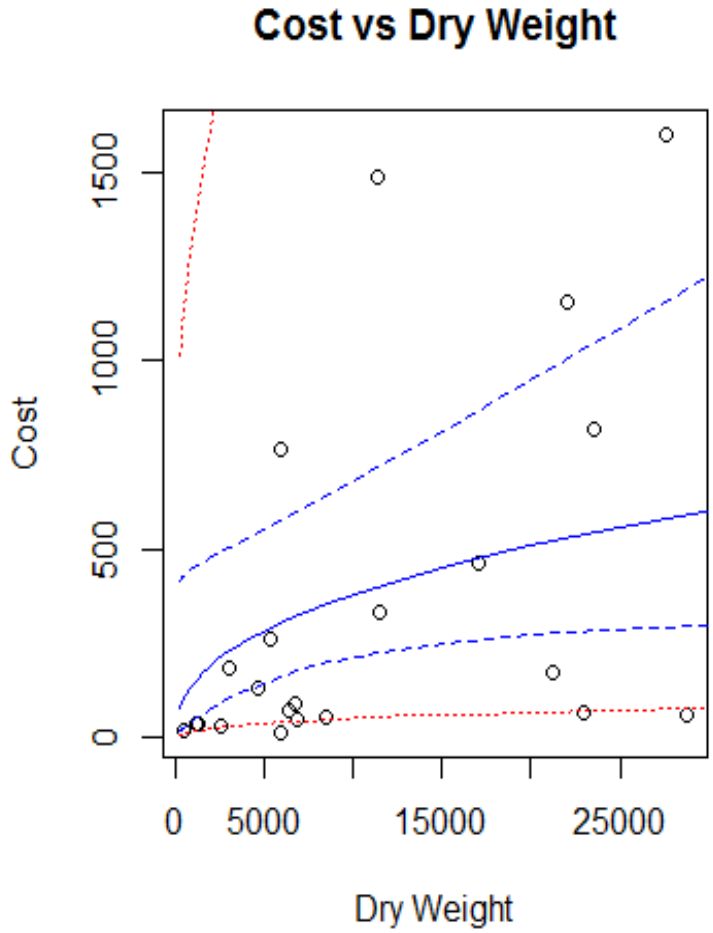
# Final Model


Cost vs Mach
lnCost
lnMach
3
4
5
6
7
-1
0
1
2
3


Cost vs Mach
Cost
Mach
0
500
1000
1500
0
5
10
15
20
25

# Final Model


Cost vs Dry Weight
lnCost
lnDry Weight
3
4
5
6
7
6
7
8
9
10


Cost vs Dry Weight
Cost
Dry Weight
0
500
1000
1500
0
5000
15000
25000

# Future X-Planes

TABLE 3. Predicted Cost for Future X-Planes

| Configuration | Point Estimate | Lower Estimate | Upper Estimate |
|---|---|---|---|
| HWB | 251.62 | 96.84 | 653.79 |
| ND8 | 159.89 | 76.22 | 335.41 |
| TBW | 164.52 | 82.12 | 329.57 |
| LBFD | 179.98 | 121.40 | 266.84 |

# Future X-Planes and X-Wings

# Summary

- Within a two-month effort the Armstrong Cost Engineering Team has gone through the full process in developing a parametric cost model.
- We have identified and collected key parameters, such as; dry weight, length, wing span, manned vs unmanned, altitude, Mach and thrust.
- We have summarized the Variables.
- We created a regression analysis on 22 CERs of the 65 X-Planes that are currently in the data base.
- We have gone through the initial stages in determining the “best fit” for R2 values.
- We have parametrically priced out several future X-Planes.
- More work needs to be done !
  - One recommendation is to stand-up a NASA Armstrong Cost Engineering Office on a non-interference basis.

# Questions

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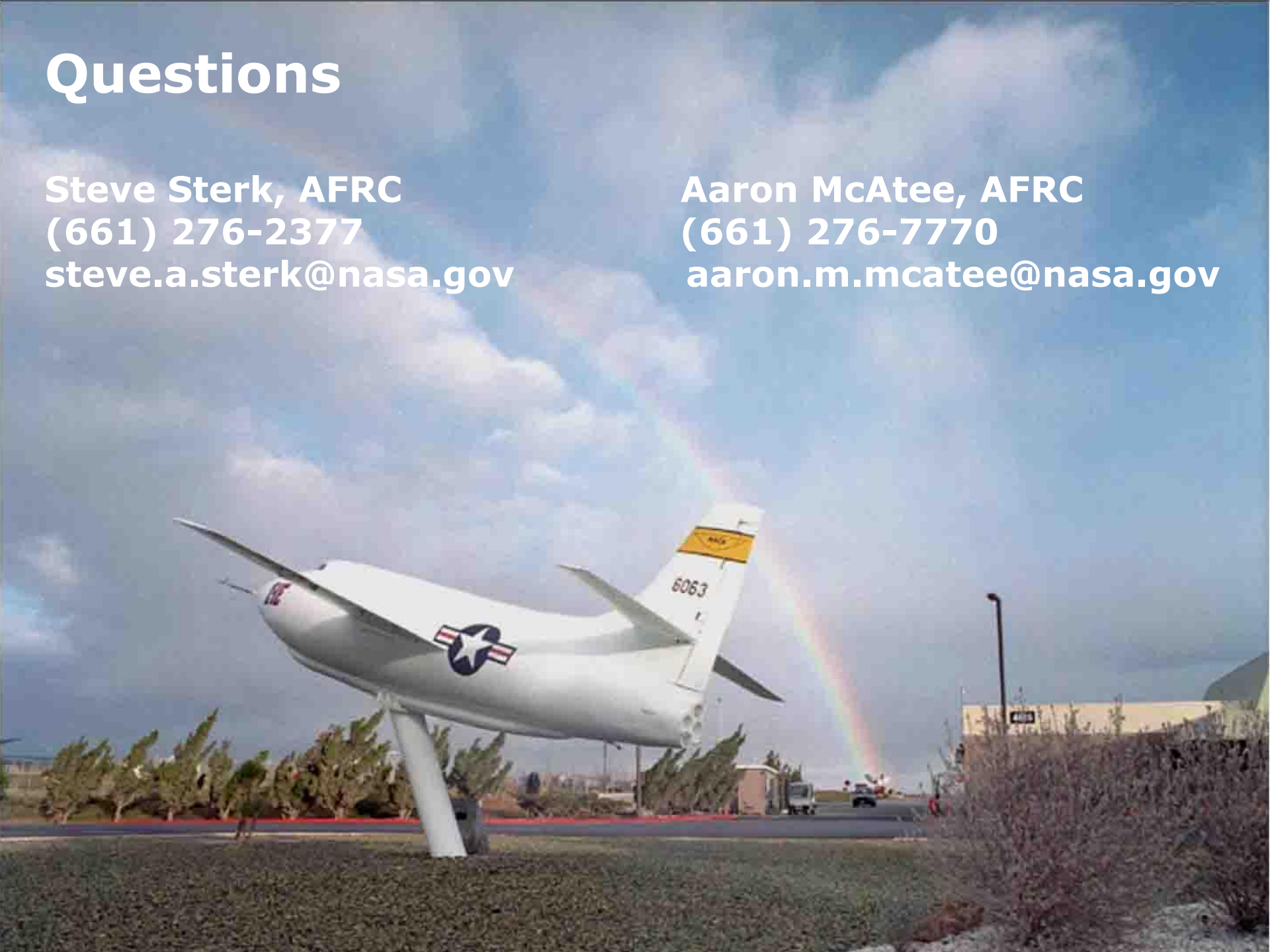
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